EXPERIMENTAL STUDY OF THE DYNAMICS OF A SPHERICAL FLAME*

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ABSTRACT

Preliminary results of an experimental study conducted to investigate the dynamic behavior of flames in explosive gases are presented. The medium was an equimolar acetylene-oxygen mixture maintained initially at a pressure of 110 torr. and room temperature in an experimental vessel 9 cm in internal diameter. Ignition was performed by means of a neodymium laser beam focused on a 0.3 mm diameter steel wire. Experimental observations were performed by the use of a stroboscopic laser-schlieren system yielding a set of photographic records of wave phenomena at a frequency of 2×10^5 frames per second. The records reveal the existence of a number of shocks which by a thorough analysis of the blast wave generated by the ignition process, are shown to be due entirely to the flame generated flow field. The capability of a flame to form blast waves in an expanding spherical geometry is thus established, providing an experimental demonstration of the significance the dynamic effects of combustion can achieve.

INTRODUCTION

The knowledge of the dynamic behavior of flames should be of central importance to the study of combustion instability. So far, however, this knowledge has not been far advanced as a consequence of the great demands of both the experimental and theoretical facilities required for its acquisition. The difficulties associated with the observation of the dynamic behavior of flames in compressible media are due to the fact that, under normal circumstances, the chemical kinetics of combustion reactions are so closely coupled with the gas-dynamic processes of the flow that it is practically impossible to discern the effects of one from the other. Moreover, in most cases the situation is complicated still further by the proximity of the ignition processes which, being basically dynamic in nature, obscure completely the dynamic effects of the flame.

Recently, thanks to the advent of lasers, much sharper ignition systems have become available than those available before. Laser induced breakdown has been already exploited by J. H. Lee and his associates (1) for the study of the dynamic processes associated with ignition of explosive gases. Presented here is a pre-

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liminary report on the study which is being currently conducted at the University of California using a similar system to that of Lee for the study of the dynamic behavior of spherical flame kernels, that is of the flame acceleration processes which are in time and space sufficiently far removed from the ignition region that its effects can be neglected. It is, in fact, with the proof of this proposition that the present paper is primarily concerned.

EXPERIMENT

The experimental chamber is presented on the photograph in Fig. 1. It is basically a steel cylinder 9 cm in internal diameter and 10 cm long, provided at both ends with optical windows 10 cm in diameter, and proper appertures for lenses to focus the laser beam, for gas handling conduits and a pressure transducer. Shown also on the photograph is a neodymium laser than delivers about 200 megawatts of power in a giant pulse approximately 20 nanoseconds in half width obtained by the use of a chemical dye as the Q-spoiler. The laser pulse was focused on a small, 0.3 mm in diameter, steel wire which under the laser irradiation provided a relatively gentle, but at the same time sufficiently sharp, energy source for ignition. It is believed that its action was more thermal in nature than electrical, so that the flame generated by its means was relatively uncontaminated by the products of an electrical discharge.

The primary source of experimental records was provided by the stroboscopic Kerr cell-modulated laser-schlieren system (2, 3) yielding a sequence of photographs taken at a frequency of 2×10^5 frames per second. Such records obtained with the use of an equimolar acetylene-oxygen mixture at an initial pressure of 110 torr (and room temperature) are given by Figs. 2 a-d. Shown there at first is the flame kernel surrounded by the front of a spherical blast wave which was generated by the ignition process. Over most of its growth the flame travel is relatively uneventful, until in the last set of records, Fig. 2d, there is evidence of a number of additional shocks which are evidently generated by the flame starting at an instant about 120μ sec after ignition.

The ability of a spherical flame kernel to generate shock waves is obviously of prime significance as a manifestation of its dynamic capabilities. To our knowledge no experimental evidence of such capabilities have been ever published before. In presenting them here for the first time, it has been, therefore, considered of some importance to demonstrate that this phenomena are due entirely to the combustion process rather than being associated with the effects of ignition. This is then the main purpose of the analysis that follows.

ANALYSIS

The experimental records provide accurate data on the trajectories of the observed wave fronts in the time-space domain. The frequency of the Kerr cell acting as the Q-spoiler for the laser cavity is controlled directly by an oscillating crystal of a time-mark generator so that the repeatability of time intervals are accurate within at least a number of nanoseconds. At the intervals of 5 microseconds this corresponds to an accuracy of 10^{-3}. The positions of the fronts in each frame were measured directly from the film by means of a spectroscopic microreader with a reading capability in microns. With our optical systems the ratio of the image on the film to object size is 0.13, for radii in millimeters this gives an accuracy better than 1%, yielding therefore the same order of magnitude for the precision in the velocity measurement.

The time-space diagram of the observed wave phenomena, deduced thus from the 32 frames of Figs. 2a-d, is shown in Fig. 3, and the corresponding front velocities, evaluated by graphical differentiation of the trajectories, are given in Fig. 4. For general orientation, included in the latter is also the Mach number of the initial shock, S_o.

With the front Mach number of an order of 1.5, the initial blast wave must be treated as one corresponding to a "non-zero counterpressure" (4). The case of such a decaying, constant energy blast wave has been recently evaluated by Korobeinikov and Chushkin[5] and the results for the three basic geometrical conditions (spherical, cylindrical and plane, corresponding, respectively, to $j = 2$, 1 and 0) and a number of specific heat ratios, γ, were published in tabular form[6]. These results have been graphically correlated by us, as shown on Figs. 5 and 6, demonstrating that all the front trajectories of the constant energy blast waves can be expressed, especially for small Mach numbers, by a single curve on the logarithmic time-space diagram, the differences associated with various values of j and γ being reflected only in appropriate shifts in the scales of coordinates.

The trajectory of shock S_o has been matched with the front of a constant energy blast wave as shown in Fig. 7 which demonstrates also that the trajectories of the shocks S_1 and S_2, appearing later in front of the flame, have a completely different character. This is brought out clearer in the plot of the logarithmic front velocity $\mu \equiv d\ln r/d\ln t$ given by Fig. 8. For a decaying, constant energy blast wave, this parameter varies from $\mu_s = 2/(j+3)$ (or 2/5 for spherical geometry) to $\mu = 1$. On the other hand, shocks S_1 and S_2 start with μ 's exceeding 3 and maintain values larger than unity throughout their existence.

From the above one can conclude that shock S_o is indeed a front of a constant energy decaying blast wave, or, in other words, its strength is not affected by the heat released by the flame. The question still remains as to what an extent is the motion of the flame front and of shocks S_1 and S_2 influenced by the flow field of the blast wave through which they evidently propagate. More specifically the portion of the blast wave under question is identified on Fig. 9 in terms of the shock front parameter $y_s \equiv 1/M_s$ and the corresponding flame coordinate $x_f \equiv r_f/r_s$, subscript f referring to the flame and s to the shock front.

Some representative particle trajectories deduced from the tables of Korobeinikov and Chushkin in this portion of the blast wave are shown on Fig. 10, and the values of all the gasdynamic parameters of the blast wave immediately ahead of the flame front, without any account taken of the flame generated flow field, are given in Fig. 11.

As it appears from the latter that, after the initial transient stage, the flow field of the blast wave ahead of the flame attains, considerably before the appearance of shock S_1, a practically steady state of zero particle velocity, undisturbed pressure, and the density approaching slowly its initial value. Thus, for all intents and purposes, the transient processes of the initial blast wave associated with ignition can be neglected, except for the small increase in the temperature reflected by the density curve. In particular, one may conclude that the motion of shocks S_1 and S_2 is, therefore, due entirely to the effects of the flame generated flow field.

CONCLUSIONS

The capability of a spherical flame to generate shock waves has been experimentally demonstrated. The unique record of the flame and, the associated with it, shock fronts has been subjected to a thorough analysis in order to establish the fact that the influence of the blast wave formed by the ignition process on the observed phenomena is negligible.

The analysis does not take into account, however, the flow field generated by the flame. Thus the gasdynamic parameters of state evaluated immediately ahead of the flame, as shown in Fig. 11, represent only their components due to the blast wave. Their actual values should be different as a consequence of the flame generated flow field.

In particular, the flame velocity in Fig. 11 is, in effect, the sum of the burning speed and the particle velocity due to the action of the flame. In a study, to be published elsewhere, of the flow fields associated with constant velocity deflagrations, we have shown, in fact, that, under the operating conditions of the experiment, the latter takes up most of the value observed experimentally, the particle velocity being of an order of 100 m/sec and the burning speed just about 3 m/sec. The increase in the flame velocity recorded in Fig. 11 just before the appearance of shock S_1 can be ascribed, most probably, to the fact that the flame became turbulent, the transition being due, in turn, to the fact that the flow field ahead of the flame, being associated with a relatively high velocity, was itself turbulent.

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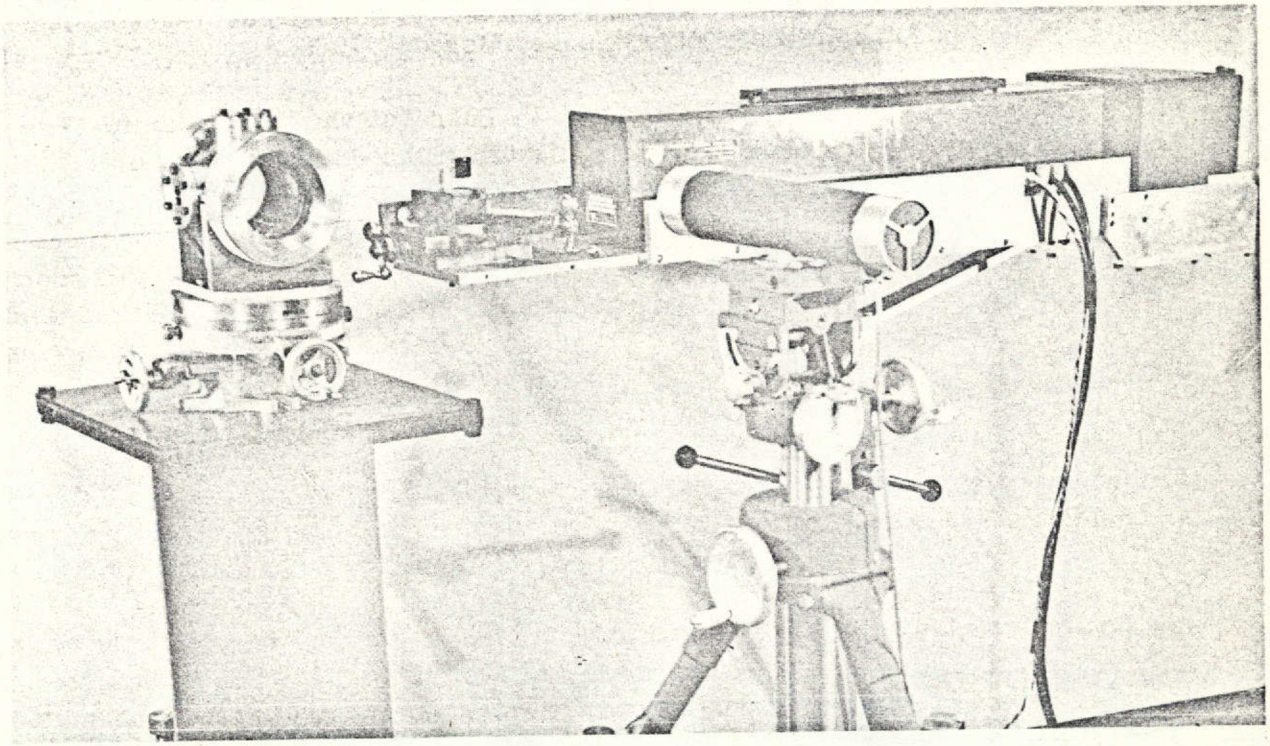

FIGURE 1. PHOTOGRAPH OF EXPERIMENTAL VESSEL IN FRONT OF NEODYMIUM LASER USED FOR IGNITION (In front is a gas laser used for optical alignment of the system).

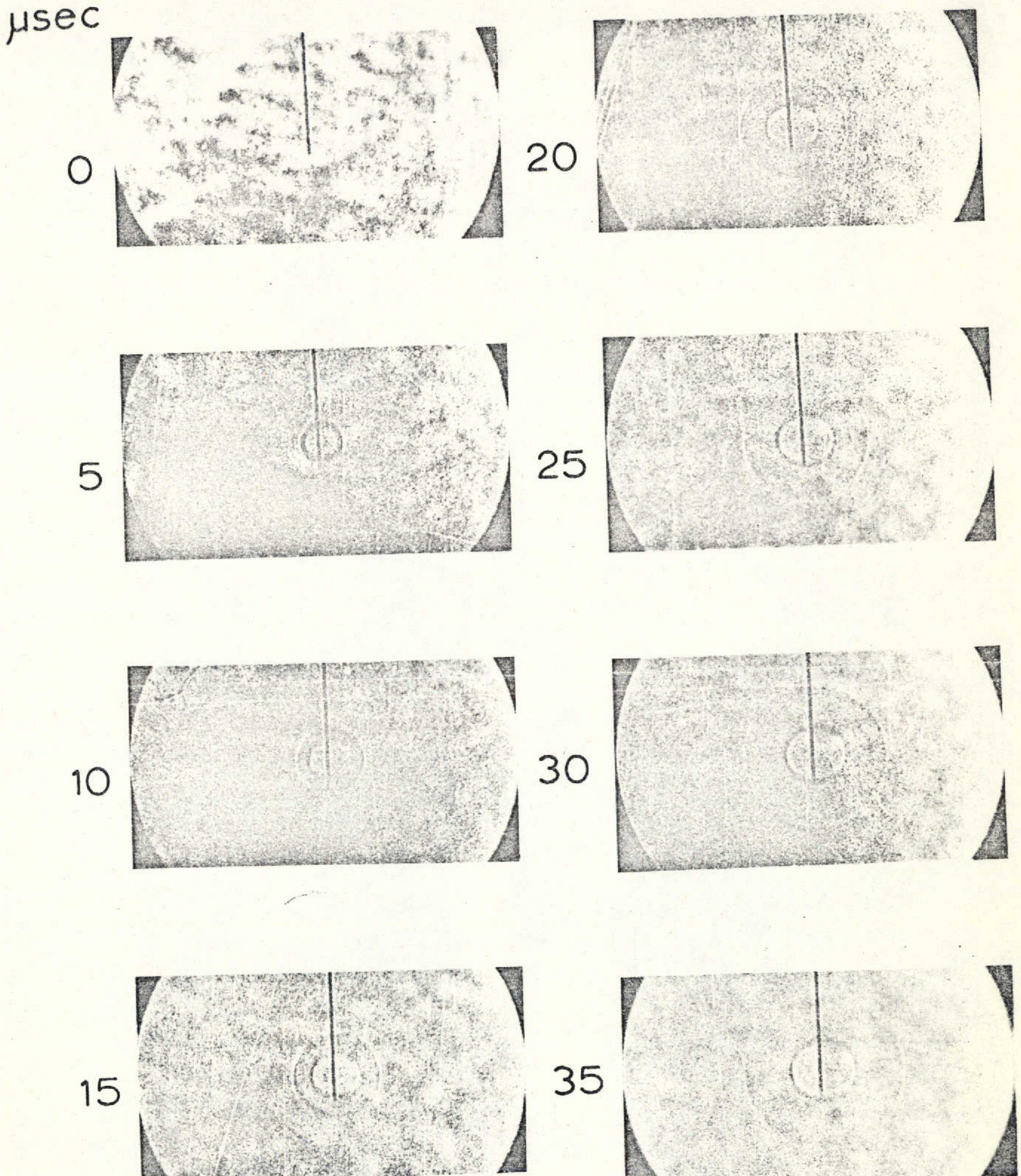

FIGURE 2. STROBOSCOPIC LASER-SCHLIEREN PHOTOGRAPHS OF WAVE PHENOMENA ASSOCIATED WITH IGNITION OF AN EQUIMOLAR ACETYLENE-OXYGEN MIXTURE INITIALLY AT A PRESSURE OF 110 TORR. AND ROOM TEMPERATURE.

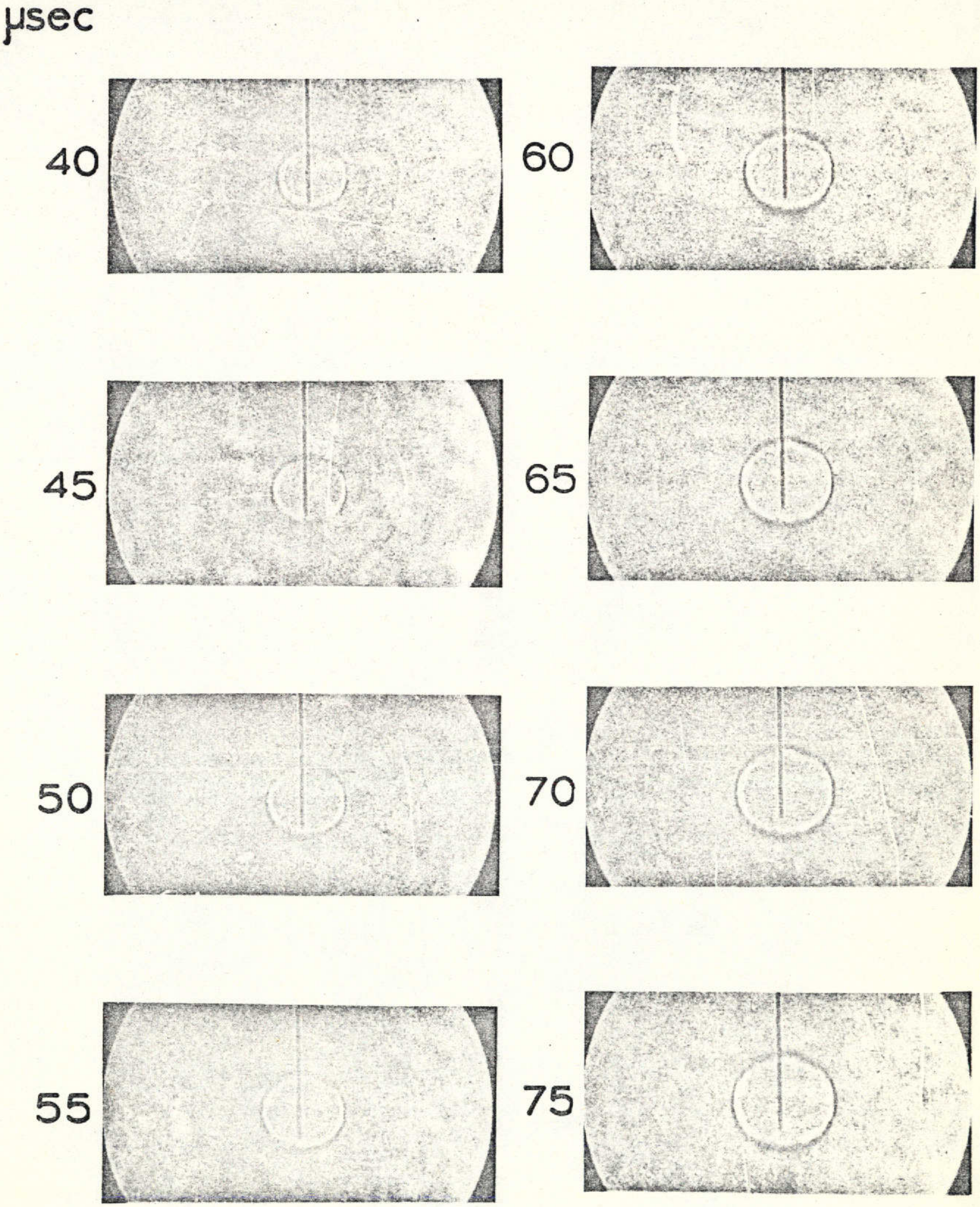

FIGURE 2A

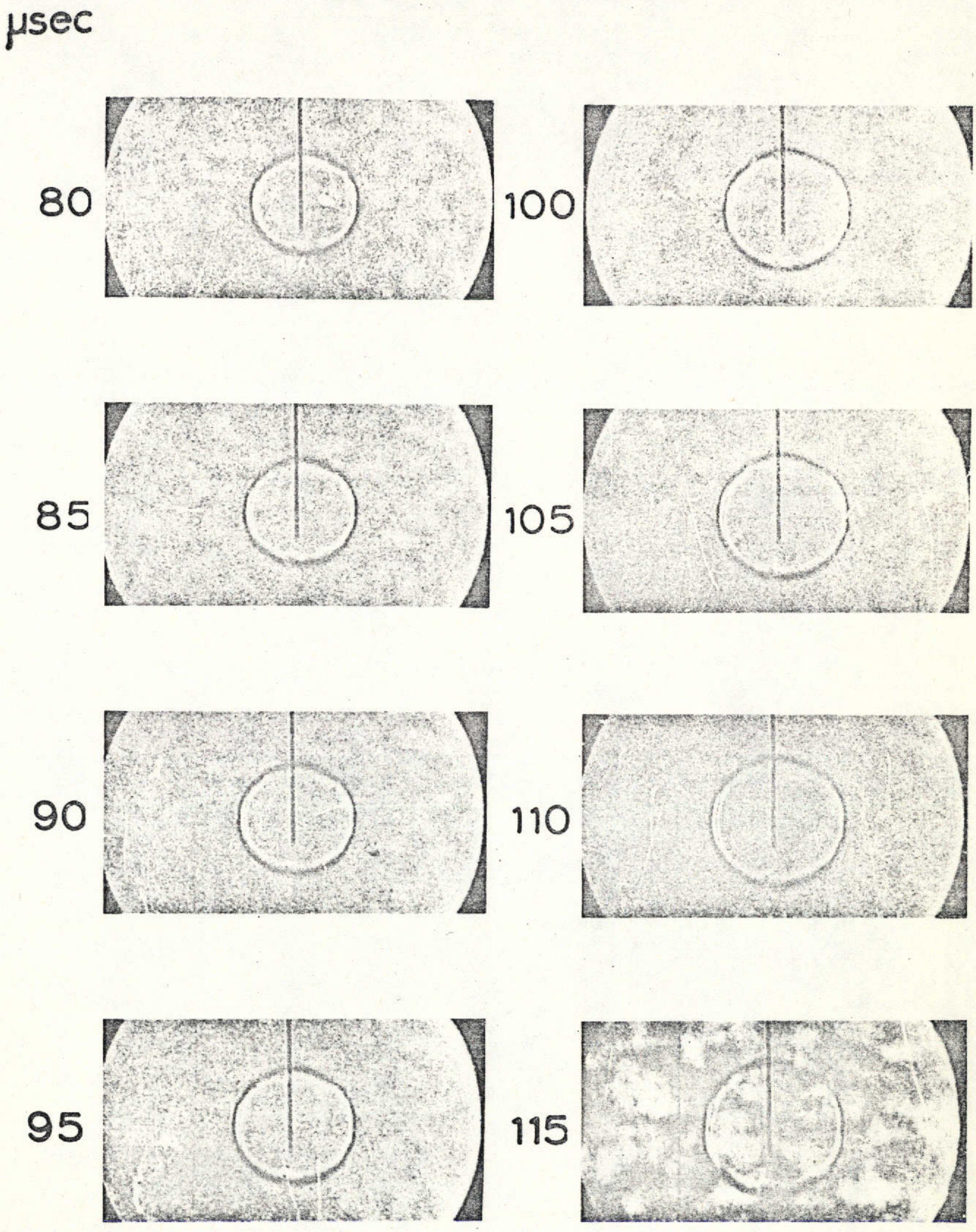

FIGURE 2B

μsec

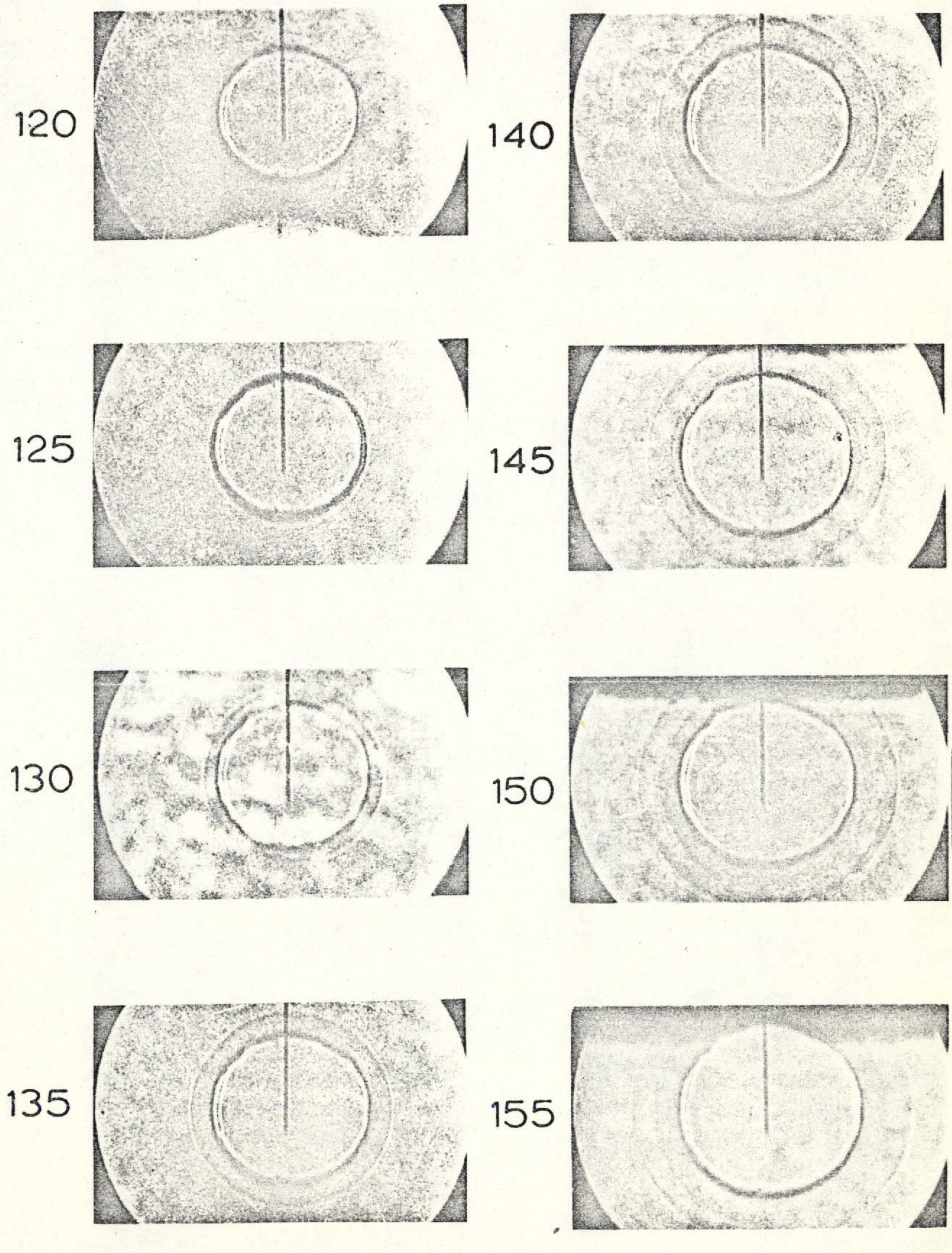

FIGURE 2C

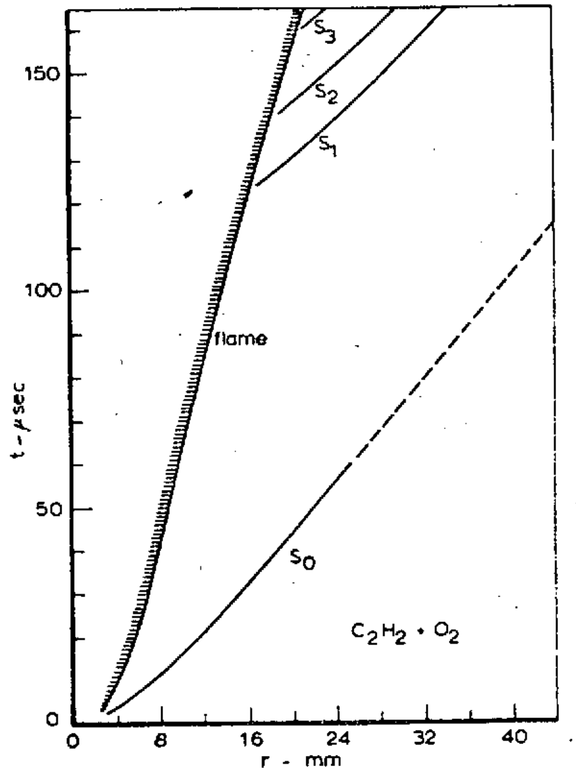

FIGURE 3. TIME-SPACE TRAJECTORIES OF WAVE FRONTS RECORDED IN FIGURE 2.

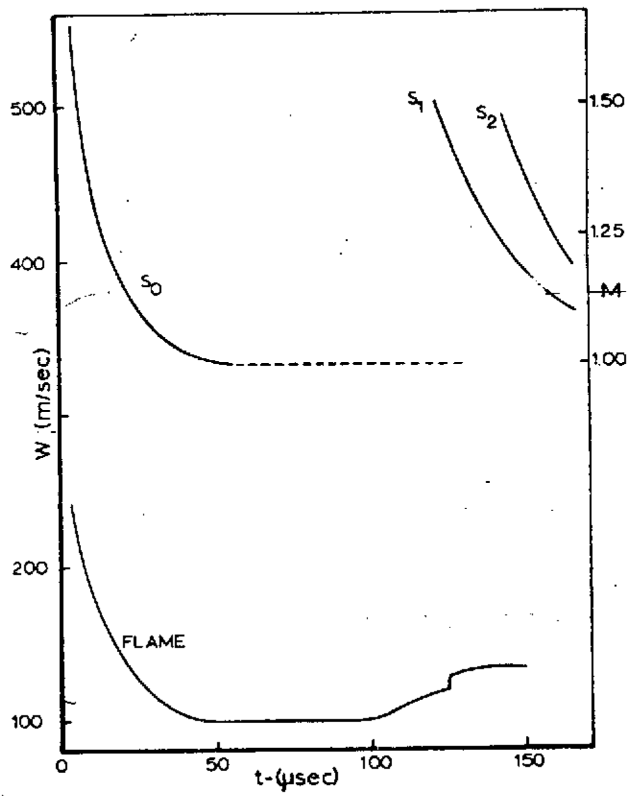

FIGURE 4. FRONT VELOCITIES.

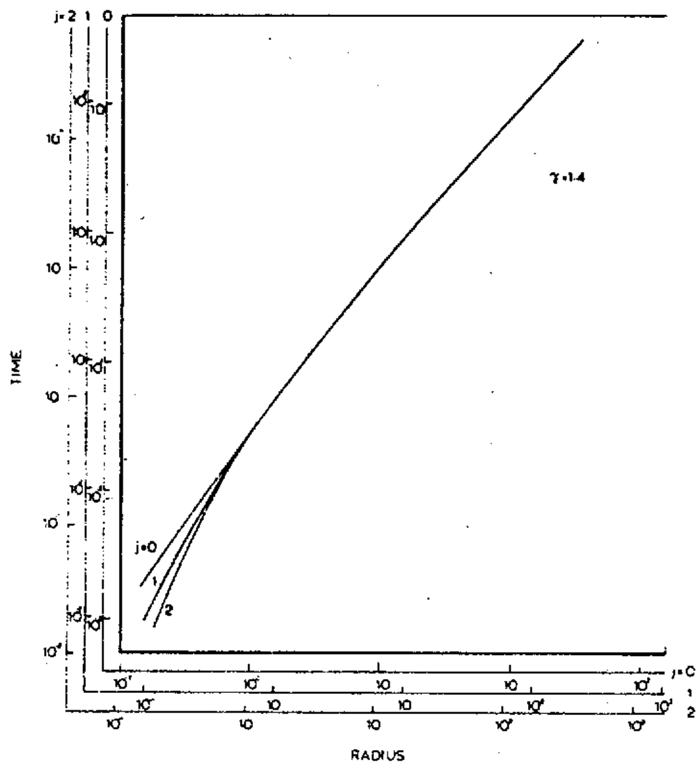

FIGURE 5. FRONT TRAJECTORIES IN LOGARITHMIC TIME-SPACE PLANE OF CONSTANT ENERGY BLAST WAVES FOR PLANE, LINE AND POINT SYMMETRICAL FLOW FIELD AND $\gamma = 1.4$ (based on data of Ref. 6).

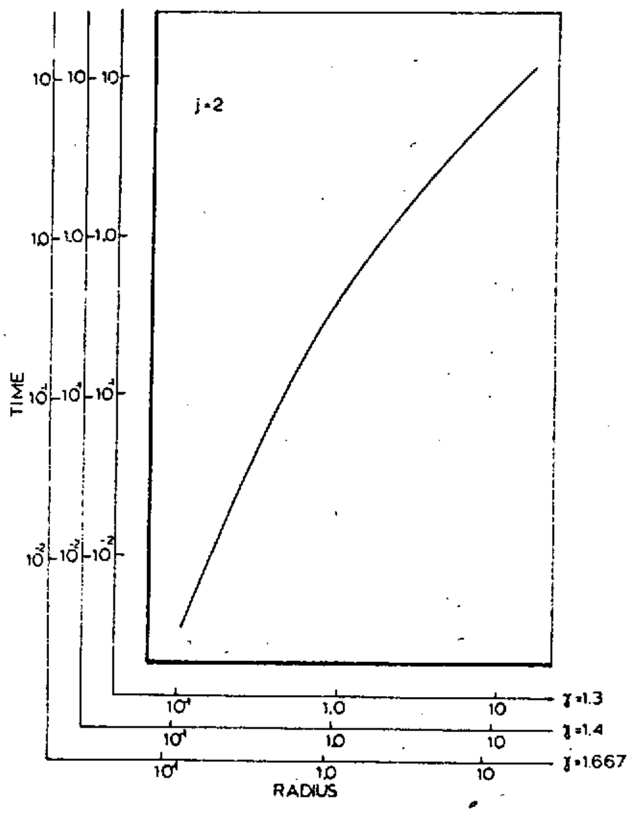

FIGURE 6. FRONT TRAJECTORIES IN LOGARITHMIC TIME-SPACE PLANE OF CONSTANT ENERGY BLAST WAVES FOR A POINT SYMMETRICAL FLOW FIELD AND $\gamma = 1.3$, 1.4, AND 1.667 (based on data of Ref. 6).

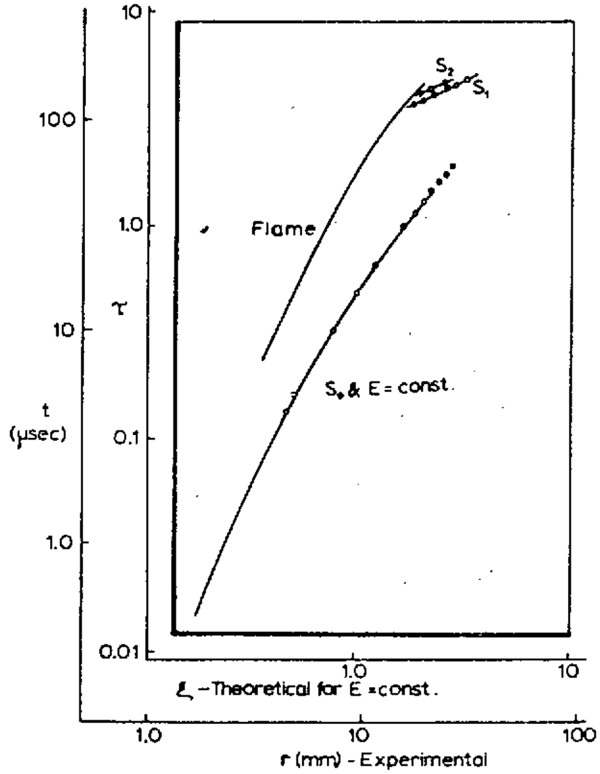

FIGURE 7. EXPERIMENTALLY OBSERVED FRONT TRAJECTORIES IN LOGARITHMIC TIME-SPACE PLANE IN COMPARISON TO THE TRAJECTORY OF A CONSTANT ENERGY BLAST WAVE.

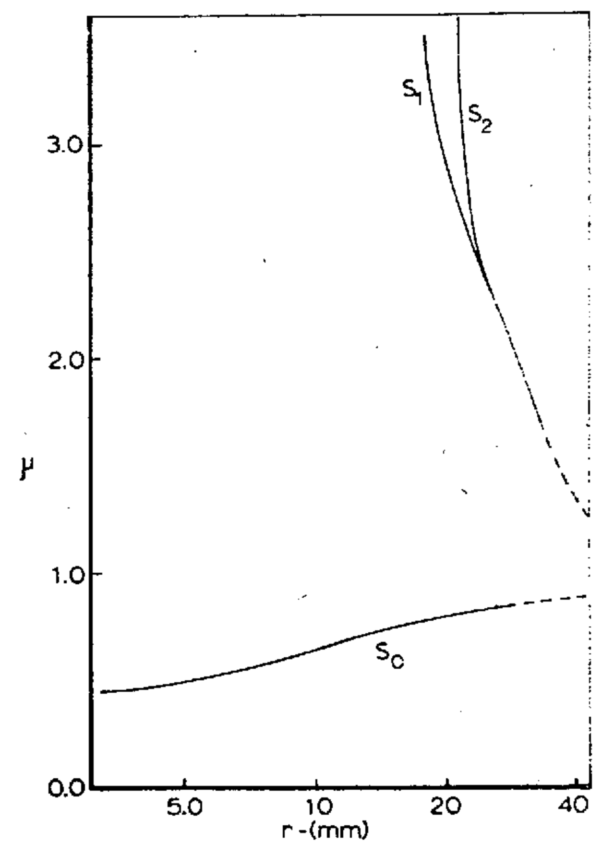

FIGURE 8. LOGARITHMIC VELOCITIES OF EXPERIMENTALLY OBSERVED SHOCK FRONTS.

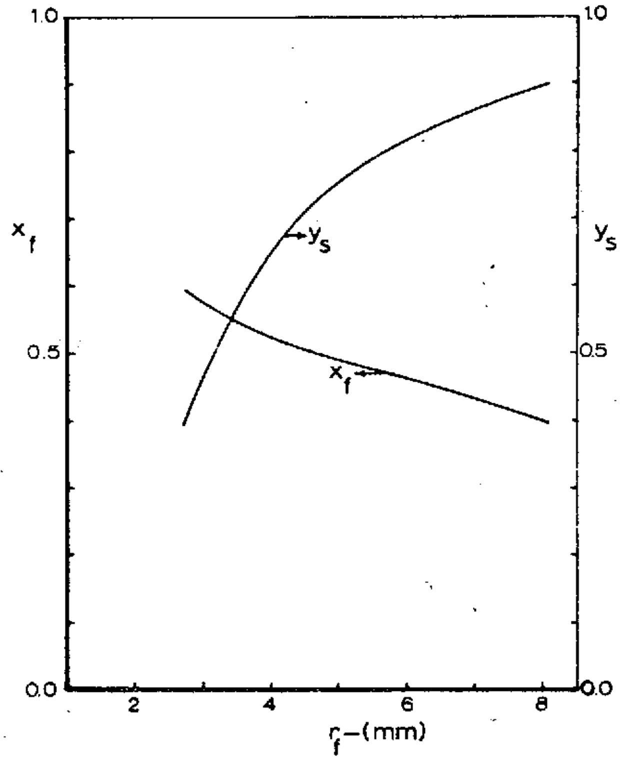

FIGURE 9. SPECIFICATION OF THE BLAST WAVE AHEAD OF THE FLAME IN TERMS OF THE VELOCITY PARAMETER OF THE FRONT, $y \equiv a_a^2/w_s^2$, AND THE FLAME POSITION COORDINATE $x_f \equiv r_f/r_s$.

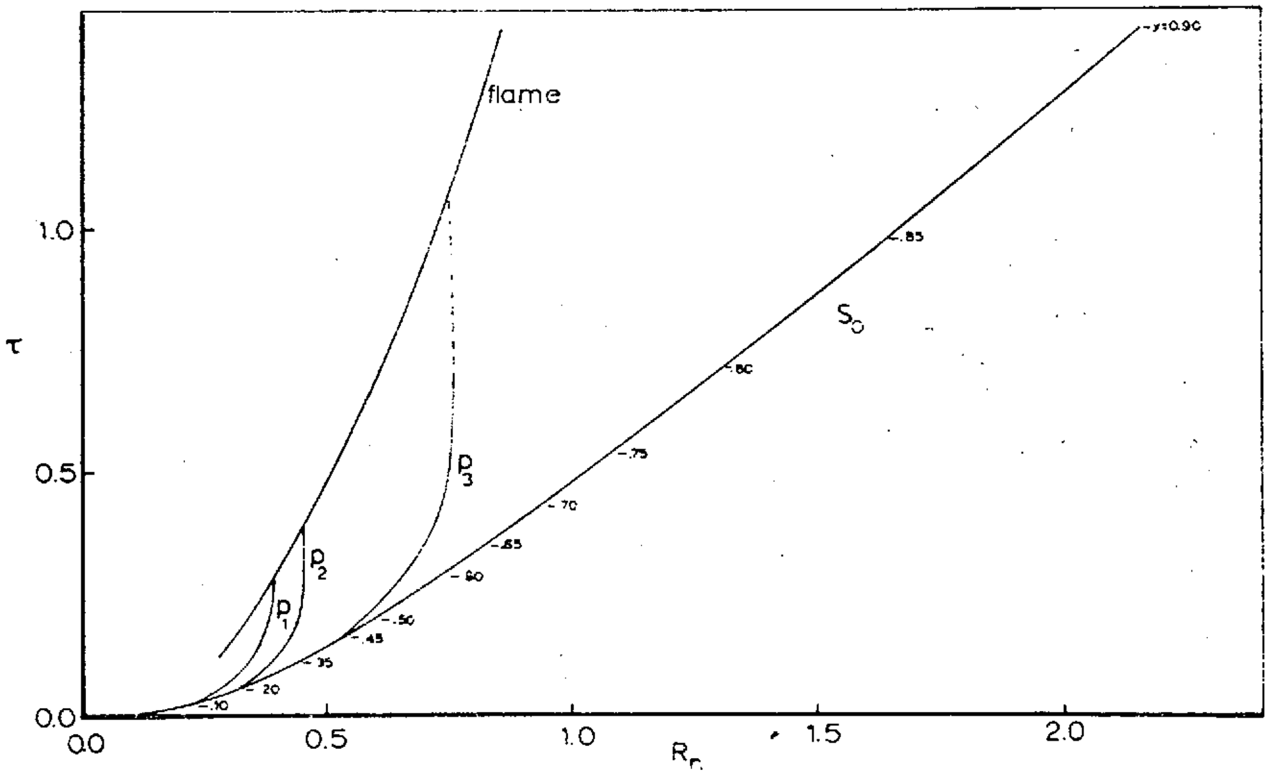

FIGURE 10. REPRESENTATIVE PARTICLE TRAJECTORIES OF THE BLAST WAVE IN THE TIME-SPACE DOMAIN.

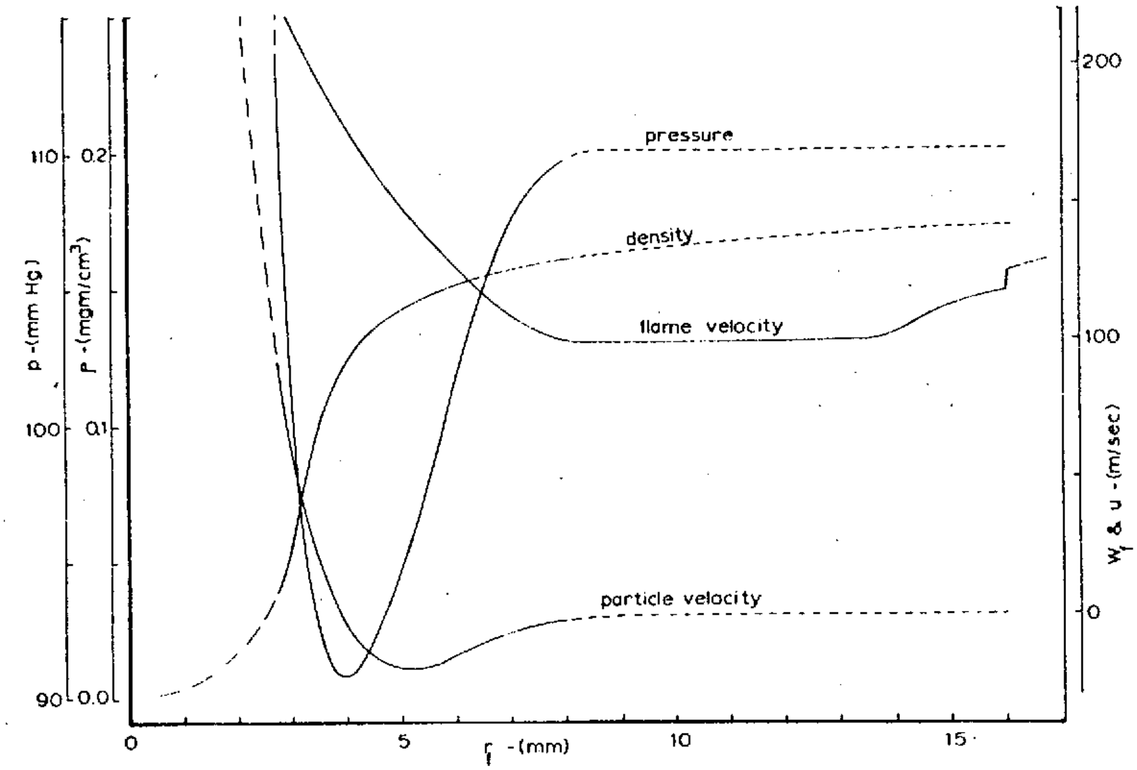

FIGURE 11. GASDYNAMIC PARAMETERS OF THE BLAST WAVE IMMEDIATELY AHEAD OF THE FLAME (without any account taken of the flame generated flow field).